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# LOG-POLAR OPTICAL COORDINATE TRANSFORMATION WITH APPLICATIONS FOR AUTOMATIC PATTERN RECOGNITION

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An important task in machine vision and target recognition is the rapid estimation of the orientation and size of an object with respect to a reference. An optical image processing system is described which converts in-plane rotation and size variations into shift properties using log-polar coordinate transforms. The optical system consists of a binary optical element, which performs the log-polar coordinate transform of the input image, a Fourier transform lens, a Michelson interferometer and a CCD camera for collecting the scale/rotation invariant output. The Michelson interferometer produces two identical patterns on the polar axis to prevent wraparound effects of the coordinate transform. Results are presented in terms of capability in estimating the rotation and size of simple images and discriminating between similar in-class and out-of-class images using the output of a binary phase-only correlator.



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# 1. Introduction

**1.1 Background.** Many pattern recognition schemes rely on matched filtering for comparing an unidentified object of interest to a known reference. The sensitivity of classical matched filters (CMFs) to distortions in the object (scale or rotation variations) requires a large library of reference filters to exhaust the entire range of possible correlation conditions. Binary phase-only filters (BPOFs) have been shown to be even more sensitive to object orientation distortions[1]. The inherent advantage of optical pattern recognition systems is the ability to process information in parallel, however, the requirements to serially process a large database of rotation and scale filters quickly negates any advantages.

Log-polar coordinate transforms are a well established technique for highlighting specific scale and rotation properties of an object of interest [2,3]. In the human vision system, the eye-to-brain mapping is a log-polar mapping process[4]. The log-polar coordinate transform presented in this paper provides a feature space where Cartesian angular position is remapped to the x-axis and where Cartesian radius is remapped to the y-axis. When the remapped image of the object of interest is used in a correlator, object variations in rotation and scale are represented as linear shifts on their respective axis of the correlation output plane. These linear shifts translate into information about the size and rotation of an object with respect to the reference filte:. In machine vision applications and image processing, estimation of the orientation and size of an object are important tasks. Others have shown how the log-polar transform can simplify the direct estimation of the time to impact for autonomous robots[4].

A number of authors propose using log-polar remapping to overcome the problem of recognizing objects which vary in rotation and scale [2,3,5,6,7,8]. In this report, we describe the design and operating characteristics of an optical image remapper which can be combined with a correlator or neural network for the purpose of determining the scale and rotation of a particular object. The advantages of the optical image remapper are the ability to perform the log-polar transformation of an image in parallel, theoretically faster than possible with a digital electronic processor. Potential applications of this optical remapper include machine vision for identifying known objects in various orientations and target recognition of objects on the battlefield from high altitude surveillance platforms.

**1.2 Approach.** Our overall goal is to develop an optical pattern recognition system. Previous work on optical pattern recognition at Rome Laboratory[9,10] has focused on the development of the BPOF optical correlator. In order to maintain an all optical pattern recognition system, we built and tested an optical coordinate transform system using diffractive optic technology. To test the usefulness of optical coordinate transformations for pattern recognition we used images at varied rotation angle and size as inputs to our optical image remapper. We then performed correlations of the remapped data with known filter data bases to determine how well the coordinate

transformed images could be recognized and if the rotation and size of the object could be determined. The correlation technique provides a measurement of distortion to the original image caused by the optical coordinate transformation and also provides a measure of how well the optical image remapper will work with an optical correlator in an overall pattern recognition system.

**1.3 Organization of Report.** This report will provide background on scale and rotation invariance using the log-polar coordinate transformation. We discuss the optical implementation of an unique image remapper, which addresses the ambiguity problem of wraparound along the rotation axis in the new feature space. We measure the capability of the optical remapping system by interfacing the output to a correlator system and measuring rotation and scale of various images with respect to a predetermined filter. We discuss these results with respect to incorporation into an optical pattern recognition system.

## 2. Scale and Rotation Invariance

**2.1 Concept.** Most optical correlation techniques, which perform a two-dimensionsal correlation at an instant in time, are intrinsically limited in performance to two-dimensional invariant processing. If the two dimensions being correlated are the x and y coordinates of a scene, then the correlator is *position invariant*. Scale, rotation and position invariant pattern recognition requires a four dimensional correlation of the scene and filter (i.e. one degree of freedom for each variable)[5]. Casasent and Psaltis proposed a feature space that would provide correlations which were invariant to scale and rotation[3]. The key to their approach is that a coordinate transformation is performed so that the scale and rotation of a given object is represented in a new feature space or coordinate axis system. This feature space would be mapped in rectangular coordinates with ln(r), where r is radial position in Cartesian coordinates, mapped along one axis and the angular position $\theta$ along the orthogonal axis. The coordinate transform in equation form[3] is represented as

$$\ln(r) = \ln (x^2 + y^2)^{\frac{1}{2}} \qquad (1)$$

$$\theta = \tan^{-1}\left(\frac{y}{x}\right) \qquad (2)$$

**2.2 Constraints.** The major limitations in using the coordinate transformation in machine vision or pattern recognition is that it only works well for a single object and the object must be centered in the x-y coordinate system before remapping into the log-polar coordinates. There are many existing digital recognition schemes that detect blobs (possible objects) within a scene and

then create a region of interest about the centroid of the object. This blob detection technique can also be perfomed using an optical correlator. In general this recognition scheme would solve the single object per scene limitation and the centering problem. Another method of centering the object within a scene is to perform a Fourier transform (FT) of the scene and record the magnitude[3]. In effect, this eliminates the linear phase terms in the spatial frequency domain which are related to the shift of the object within the spatial domain.

**2.3 Implementation.** There are a number of means of implementing the coordinate transformation. Electronic hardware has been designed and built for the purpose of coordinate transformations[7]. Optical techniques using computer generated holograms (CGHs) have also been widely discussed in the literature[6,8]. One limitation of past designs is that wraparound effects along the $\theta$-axis cause a clipping of the image or ambiguity in the feature space. This ambiguity presents problems for a correlator system because the correlator's filter is designed based on a specific angular orientation of the object. As the object is rotated the features wraparound the $\theta$-axis. While correlation will still occur, the magnitude and location of the correlation peak may significantly vary depending on the original images rotation. Asselin and Arsenault described a technique for rotation invariance by superimposing two coordinate transforms side-by-side along the $\theta$-axis[8]. We have applied this technique to the scale and rotation problem. We designed a system which overcomes the wraparound effects in rotation and *is invariant* to scale changes.

## 3. Optical image remapper

The coordinate transformation is performed by the combination of a CGH and a FT lens. The CGH has a phase transmission $\phi(x,y)$ given by

$$\phi(x,y) = \left(\frac{-2\pi x_0}{\lambda f_L}\right) \left[x \bullet \ln(x^2 + y^2)^{\frac{1}{2}} - y \bullet \tan^{-1}\left(\frac{y}{x}\right) - x\right] \tag{3}$$

where $x_0$ is a constant of the same units as x and y, $\lambda$ is the light source wavelength, and $f_L$ is focal length of the FT lens. Davidson, et al[11] describe a technique where the CGH can be implemented without the use of the FT lens. The CGH used in the experimental set-up is a binary phase level device with 1000 points each for x and y in a feature space of a 10 mm$^2$. The constant $x_0$ is set to 1 $\mu$m. The design wavelength is 632.8 nm and the FT lens design focal length is 200 mm. An optical image of the transparent CGH device is shown in Fig.1.

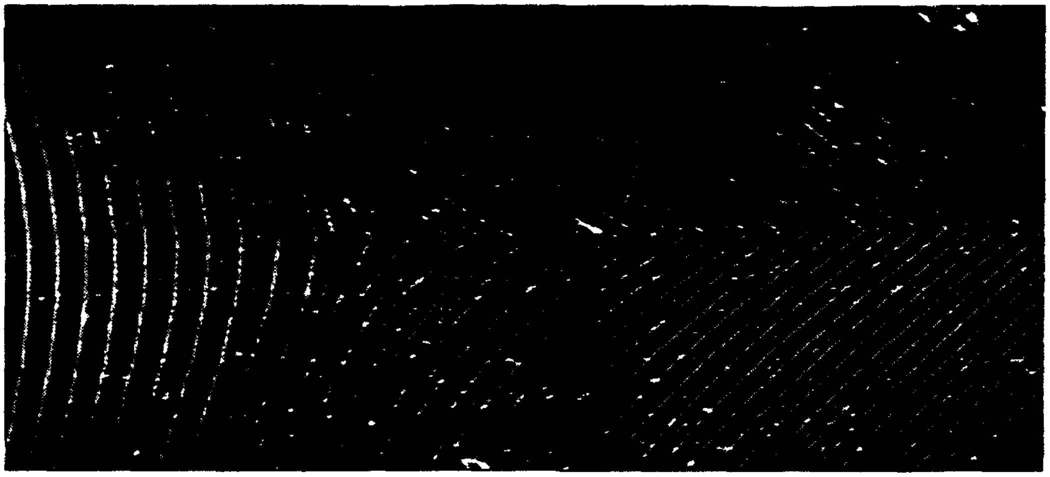


Fig.1. Optical image at 100X magnification of the centermost portion of the CGH used for the log-polar coordinate transform. The discontinuity line is visible along the horizontal axis for the values of x =0.

Our system for implementing the coordinate transformation with the CGH is shown in Fig. 2. The input image modulates the laser light by using a spatial light modulator (SLM), however, in our experimental set-up we used slide transparencies mounted in a rotational stage.

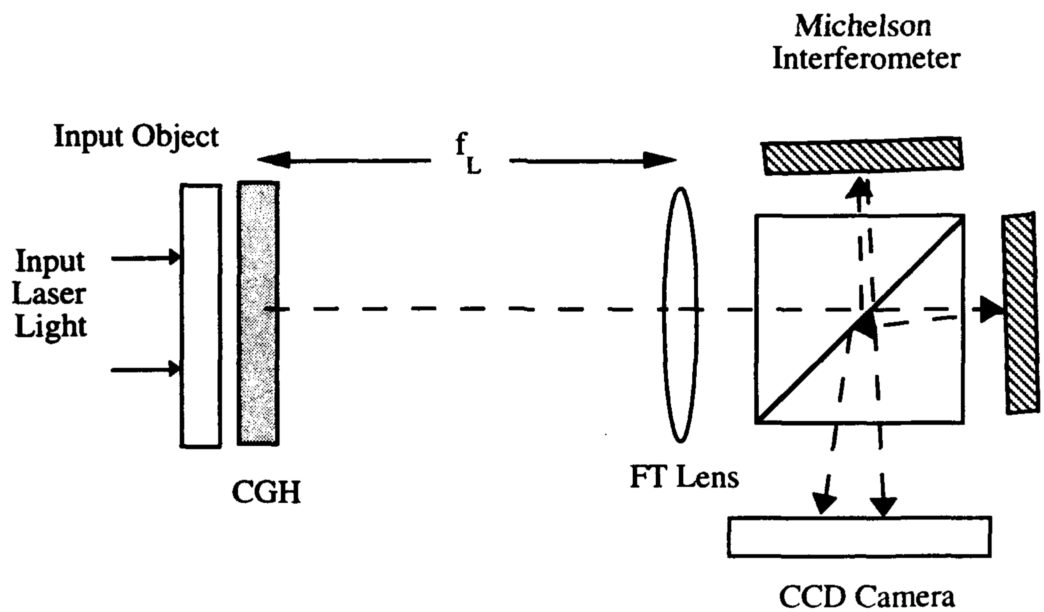



Fig. 2. Optical system for performing the coordinate transformation. The computer generated hologram (CGH) and Fourier transform (FT) lens perform the ln(r)-θ coordinate transform while the Michelson interferometer produces a dual image side-by-side along the θ-axis.

The CGH is placed in close proximity to the input SLM to minimize diffraction effects. A Michelson interferometer (shown in Fig. 2) is used to obtain the superimposed images of the coordinate transformation in the Fourier plane of the FT lens . The Michelson interferometer produces two identical patterns on the polar axis by displacing the interferometric path with respect to the horizontal axis. There is a slight region of interference between the two paths where overlap occurs. This interference causes a fringe pattern which degrades the FT image slightly. A CCD camera collects the intensity of the coordinate transform output at a distance $f_L$ from the lens.

The output of the CCD camera can be used as the input to a correlator to identify rotation and scale of the object. Our goal is to use the coordinate transform as an input to an optical BPOF correlator. The concept of the proposed optical image remapper used with a BPOF optical correlator is shown in Fig. 3.

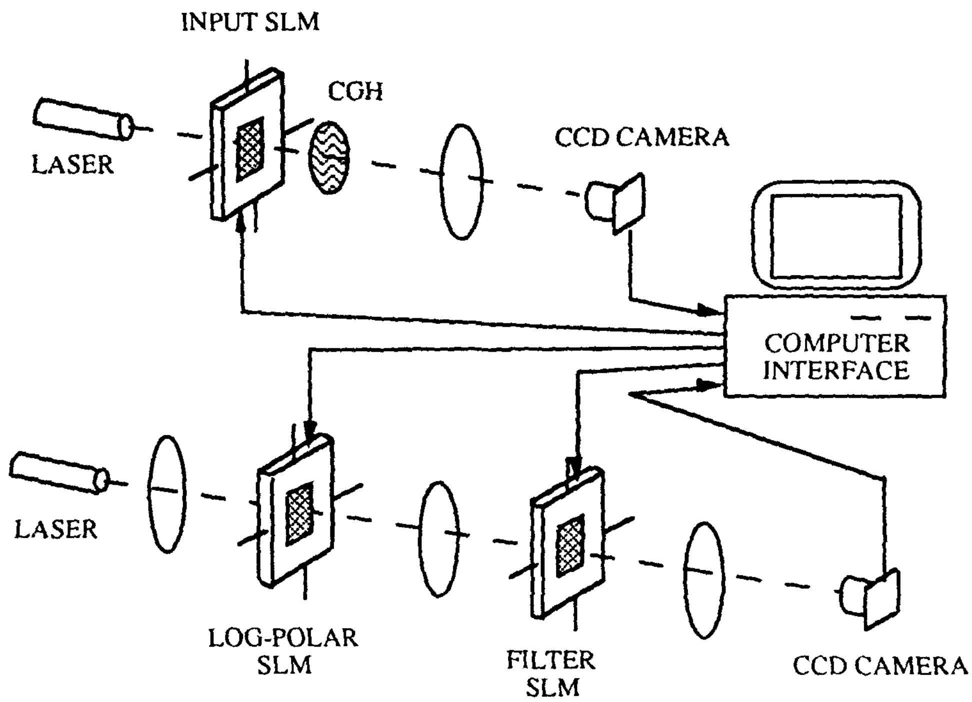



Fig. 3. Concept of proposed optical system for performing scale and rotation invariant pattern recognition.

The BPOF is used because it has also been found to be very sensitive to scale and rotation variations[1] and it provides a higher and narrower correlation peak and improved discrimination compared to the classical matched filter. To simulate the performance of the optical BPOF correlator we used a MATLAB program (see Appendix A) to perform the BPOF correlation. The filters used in the simulation were created using only half of the coordinate transform image along

the θ-axis. Only half the coordinate transformation is required because of the image replication in our optical coordinate transform system. In our experiments, we created the BPOFs (see Appendix B) by thresholding on the real value of the computed fast Fourier transform (FFT) of the reference image[12]. This is referred to as a cosine BPOF.

The computer simulation of the correlation is then performed on data collected from the optical image remapper for a set of rotated and scaled objects. A computer simulation also identifies the highest peak location and calculates the signal-to-noise ratio (SNR) for the given peak. We used the following definition of SNR[13] for our computer simulations

$$\mathrm{SNR} = \frac{I_{max}}{\mathrm{rms}(I_{(<0.5 \cdot I_{max})})} \tag{4}$$

where $I_{max}$ is the peak intensity and rms is the root mean square of the intensity I less than 50% of the peak intensity. The SNR is the ratio of the maximum intensity of the correlation peak divided by the rms of all pixels below half the height of the correlation peak.

## 4. Results and Discussion

The peak location and SNR were performed on four different objects: a B-52 bomber, an open ended wrench, an adjustable wrench, and a pair of wire cutters. The simulations were performed to measure both in-class and out-of-class correlations of similar objects for determining the recognition ability of the proposed system. During this effort, we used two figures of merit for evaluating the optical coordinate transform system presented in this paper. We have provided the remapped images of the B-52 bomber and the open ended wrench. However, these images provide only a qualitative perspective of the optical remapper's capability. Because the CGH used for the coordinate transform is a binary device, we expect some errors to occur in the remapping. The Michelson interferometer will also introduce errors, especially at the overlap region of the duplicated image. A correlation is used to compare various coordinate transforms for images of various rotation and scale. The first figure of merit is the ability of the correlator to identify the scale and rotation of an object from the remapped image. The SNR of the correlation result is also measured to determine the likelihood of a correct identification. The second figure of merit is the difference in the SNR of the correlation result for similar but out-of-class images at various rotation and scales. The combination of these two figures of merit give an accurate estimate of how well the technique will work for correctly identifying unknown objects using a rotation and scale invariant correlator. The measurements of correlation peak location for rotation were performed over a range of 0 to 360 degrees in rotation and 50% to 125% in scale. The comparison of SNR for similar but out-of-class images were performed over a range of 0 to 360 degrees in rotation.

**4.1 B-52 Bomber (Rotation Invariance).** The first two images used in the simulation were the B-52 bomber and the open ended wrench. Fig. 4 shows the first input image, a B-52 bomber, in its x-y spatial dimension and in its coordinate transform representation in the ln(r)-θ coordinate system performed with the optical system of Fig. 1. In Fig. 4(b), the tail section of the B-52 is in the center of image with two replicas of the wing structure and the nose of the aircraft shown to either side along the θ-axis. As can be seen in Fig. 4(b), we are unable to

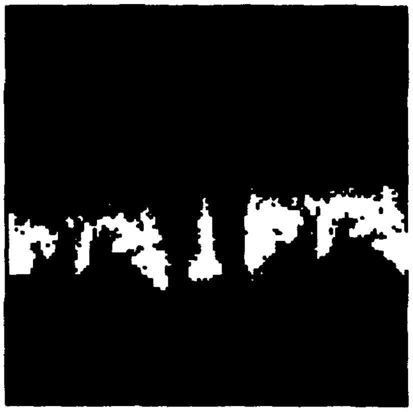




Fig. 4. B-52 bomber image a) x-y feature space and b) ln(r)-θ feature space.

capture two full replicas of the coordinate transform of the B-52 because of the limits in the size of the aperture of our CCD camera. This may result in reduced performance of the correlator caused by not having a full replication of the remapped B-52 which corresponds to our selected filter. Fig. 5 is a plot of the correlation peak location versus rotation of the B-52 with respect to the filter reference orientation which is at 20 degrees for this data. The linear relationship between peak location and rotation angle highlights the usefulness of this technique for determining rotation of an object. There is a discontinuity in the linear relationship caused by angular repetition. Another measure of the correlation versus rotation result is in terms of SNR which is shown in Fig. 6.

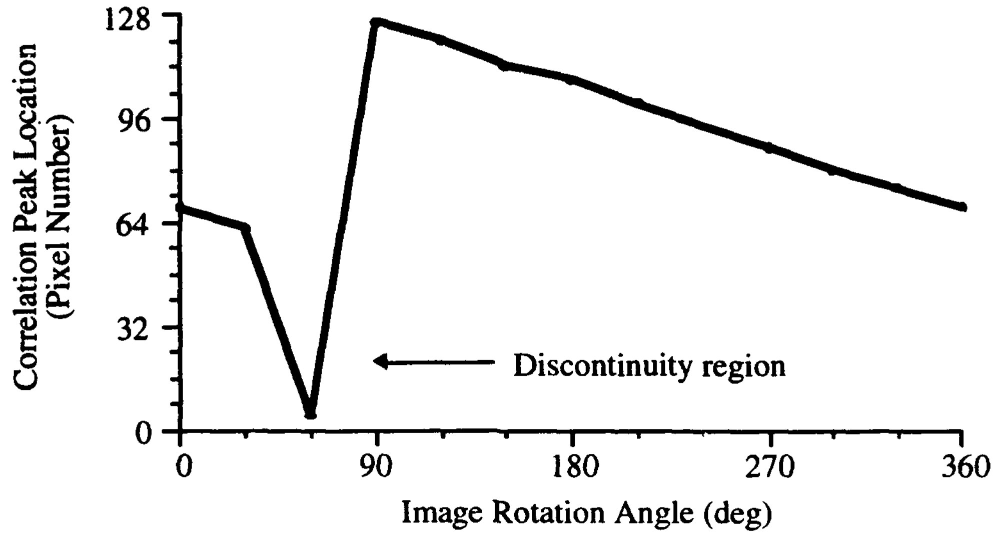



Fig. 5. Plot of correlation peak location versus actual image rotation angle of the B-52 bomber. The discontinuity region is caused by wraparound along the θ-axis and the lack of two complete images. The filter is at a reference rotation of 20 degrees.

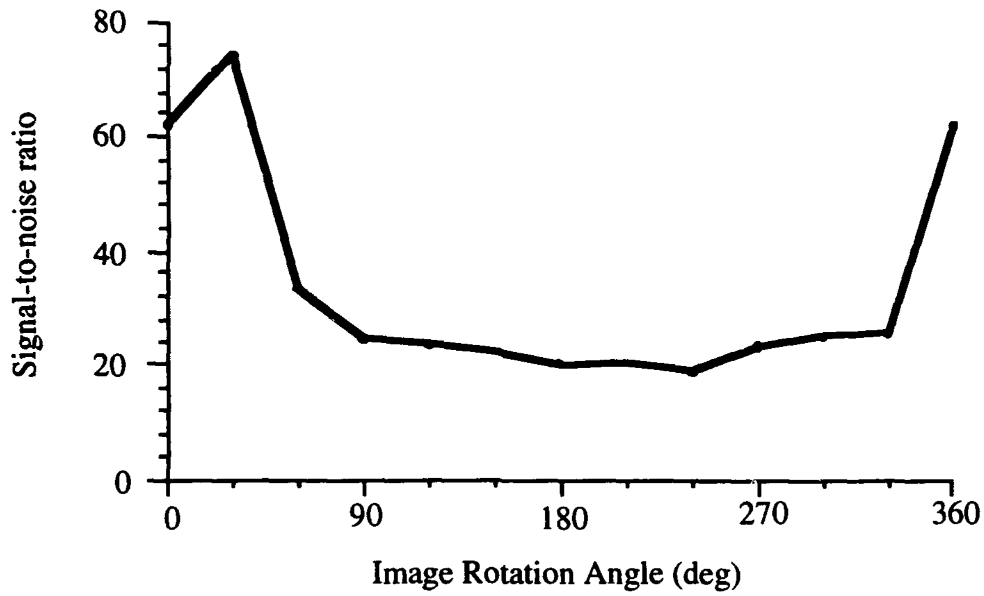
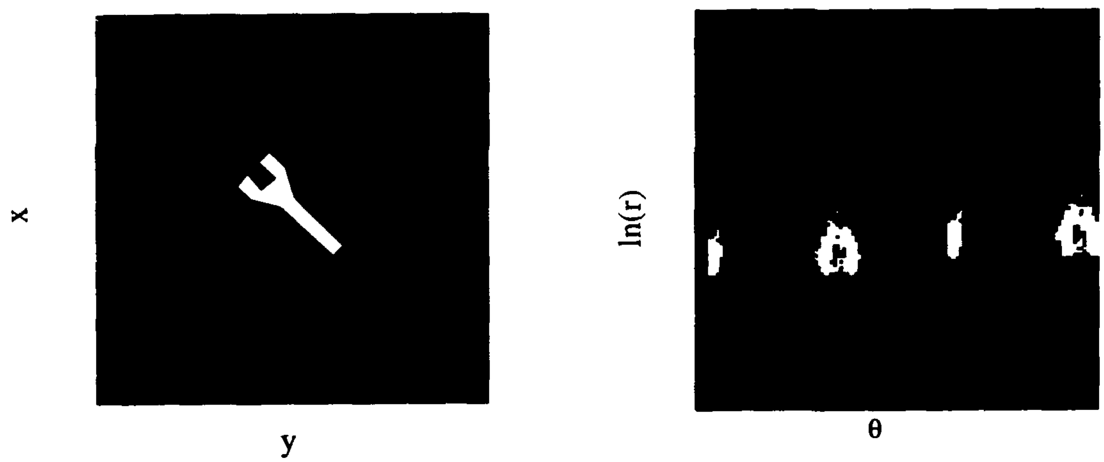



Fig. 6. Plot of signal-to-noise ratio of correlation results versus rotation angle of the B-52 bomber. The filter was at a reference rotation of 20 degrees.

As can be seen in this figure, the SNR is high near the autocorrelation with the filter at 20 degrees and falls off to a steady state value for other rotation angle. The decrease in SNR is expected given the changes in the coordinate transformed image as the object is rotated. The effects of not

having two complete images can not be quantitatively evaluated, however, some reduction in correlation SNR is possible. Another aspect which affects SNR is the fact that for most cases two correlation peaks exist because of the dual image in the input plane. This degrades the SNR based on the definition we are using. Further study of the CGH is necessary to determine if more phase levels will improve the accuracy in transforming the image.

**4.2 Open ended Wrench.** Fig.7 shows the second input into the optical transform system which is an open ended wrench, in both its x-y and coordinate transform planes. In Fig. 7(b) we are able to show the collection of two complete coordinate transform images of the wrench.




a) b)

Fig.7. Open ended wrench image a) x-y feature space and b) ln(r)-θ feature space.

However, while rotating the wrench, we observed there were orientations when two complete images were not present.

**4.2.1 Rotation Invariance.** The results in Fig. 8, which is a plot of the correlation peak location versus rotation angle of the wrench, show that a discontinuity region exists as expected. However, the plot of Fig. 8 shows a linear relationship exists between the peak location and rotation angle of the wrench. This linear relationship suggests the orientation of the wrench can be determined from the correlation data.

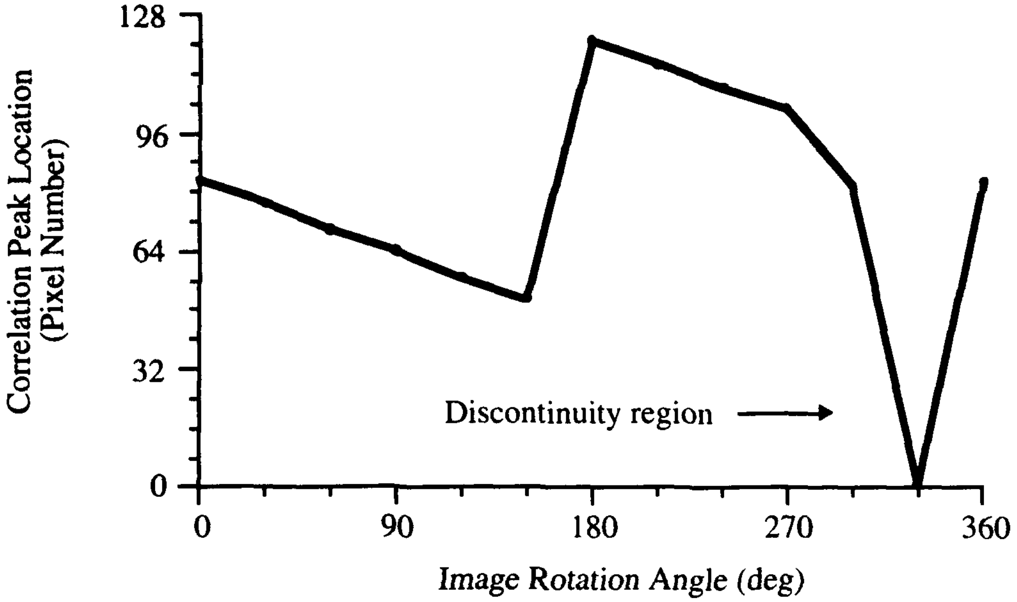



Fig. 8. Plot of correlation peak location versus actual image rotation angle of the open ended wrench. The discontinuity region is caused by lack of full image and wraparound the θ-axis. The filter is at a reference rotation of 90 degrees.

There is also a discontinuity region in the plot which is expected in our experimental set-up. Fig. 9 is a plot of the SNR versus rotation angle.

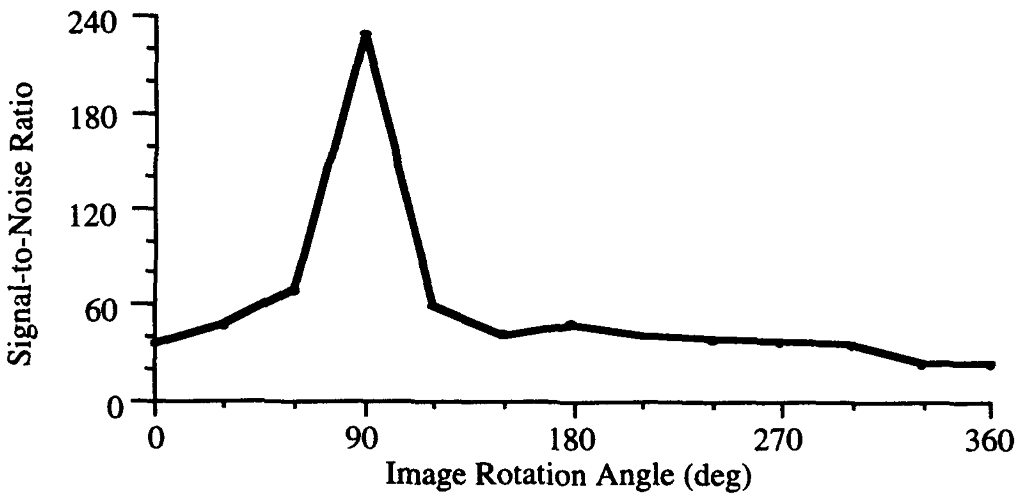



Fig. 9. Plot of signal-to-noise ratio of correlation results versus rotation angle of the open ended wrench. The filter was at a reference rotation of 90 degrees.

As can be seen in this figure, the SNR is very high for rotations which are close to the filter orientation but decreases to a steady state value of around 25 as one digresses from the filter orientation. This matches the results obtained with the B-52 bomber input and is likely caused by the same limitations in our optical remapping system.

**4.2.2. Scale Invariance.** We also tested the optical image remapper's ability to provide scale invariant images to a correlator system. Four scaled versions of the wrench were coordinate transformed and compared with the filter used in the previous rotation measurements. Fig. 10 is a plot of the correlation peak location versus size of the wrench.

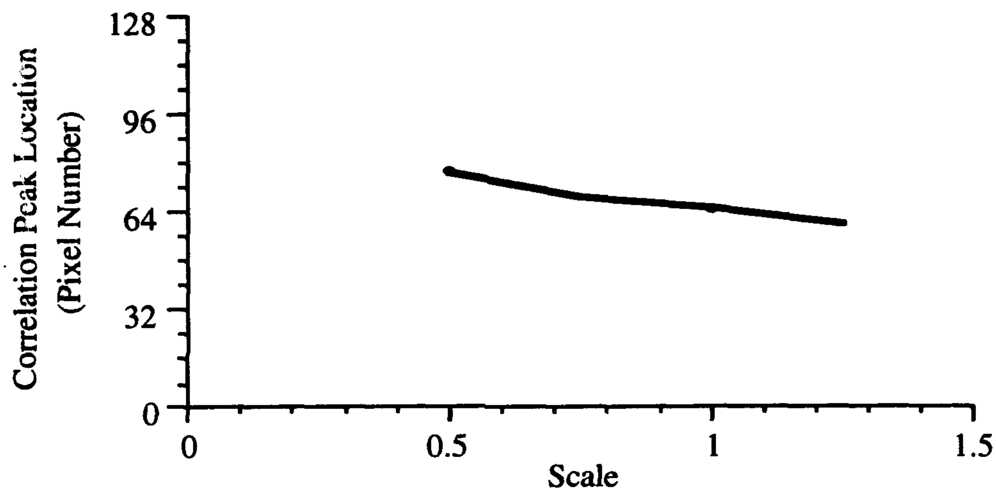



Fig. 10. Plot of correlation peak location versus actual scale of the open ended wrench. The filter is at a reference scale of 1.0.

Again a linear relationship exists with respect to peak location versus known size. For this data we do not expect to see regions of discontinuity, because there are no wraparound effects. The major limitation is the variation in scale obtainable without overfilling the CGH aperture of 10 $mm^2$. Fig. 11 is a plot of the SNR versus the different scaled wrenches. As in the rotation results, the SNR is highest at the autocorrelation of the image scale and filter scale, but decreases as the scale digresses from the filters size. The scale measurements are the hardest to perform without a reprogrammable such as an SLM to enter images into the optical remapper. Also, the magnitude of the scale distortion in Cartesian coordinates results in a smaller shift in log coordinates compared to the size of the shift caused by rotation distortions.

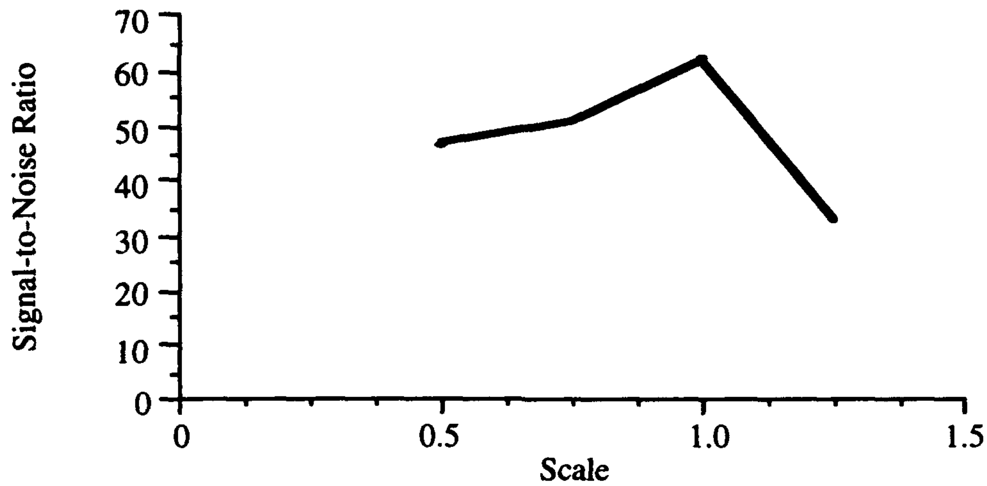



Fig. 11. Plot of the signal-to-noise ratio of the correlation results versus scale of the open ended wrench. The filter is at a reference scale of 1.0.

**4.3 In-class and Out-of-class Images.** To provide a more realistic test situation in-class and out-of-class images, which are very similar, are optically remapped and the corresponding signal-to-noise ratio and peak location data for varying angles of rotation are measured. The two images used in this simulation are an adjustable wrench shown in Fig. 12(a) and a pair of wire cutters shown in Fig. 12(b).

a) b)

Fig. 12. Input images for in-class and out-of-class measurements a) adjustable wrench and b) wire cutters

The filter used in these correlation simulations is the adjustable wrench at an image rotation angle of 90 degrees with respect to the wrench in Fig. 12a. Using this filter, the correlation SNR for input images of the adjustable wrench and the wire cutters are plotted in Fig. 13. As seen in this figure, the SNR measurements for the adjustable wrench input is high near the autocorrelation with the filter at 90 degrees of rotation and falls of to a steady state value for other rotation angles. The decrease in SNR is expected given the changes in the coordinate transformed image as the object is rotated. For the wire cutter input image, the SNR from the correlation simulation is lower than that for the wrench for all angles of rotation. Therefore, a pattern recognition system should be able to discriminate between the adjustable wrench and the wire cutters.

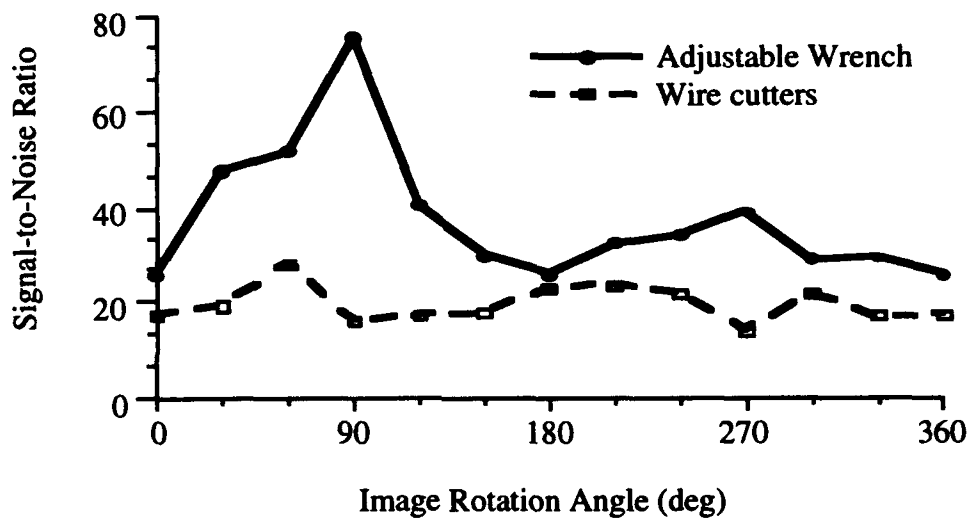



Fig. 13. Plot of the signal-to-noise ratio of the correlation results for the adjustable wrench and the wire cutters versus rotation angle. The filter is formed from the adjustable wrench at a rotation angle of 90 degrees.

Further study of the CGH is necessary to determine if more phase levels will improve the accuracy in transforming the image. Another aspect which effects SNR is the fact that for most cases two correlation peaks exist because of the dual image in the input plane. This degrades the SNR of in-class correlation versus the out-of-class correlation based on the definition we are using for SNR.

**4.4 Discussion.** The experimental and simulated results show the usefulness of performing a log-polar remapping of an image of interest. The results show that a pattern recognition system would have a high probability of discerning an objects scale and rotation based on a correlation peak's location in a two-dimensional grid. The discrimination ability of a pattern recognition system is still in question based on the results shown in this report. Specifically, similar objects

correlation SNRs are too close in magnitude for accurate image identification. Limitations in the current optical image remapper design include the number of phase levels in the CGH and the viewing size of the CCD camera. An increase in the number of phase levels in the CGH from two would improve the accuracy at which the image is remapped. The $\theta$-axis dimension of the CCD camera needs to be increased to handle the duplicate coordinate transformation pattern. The alleviation of the wraparound effect causes a trade-off in signal-to-noise ratio, because there are now up to three regions with possible correlation peaks instead of just one. The autocorrelation SNR is much higher and is the expected SNR value across the range of rotation angles for a perfect system. If further research can improve the SNR at all possible rotations for an in-class image, then the technique would be more promising. The optical image remapping system's speed is limited by the frame time of the input SLM and the readout time of the CCD camera. Further advances in SLMs are necessary to improve resolution, contrast, and frame time for an optical implementation to be reasonable. An alternative approach is to develop a CCD sensor which performs the log-polar coordinate transform.[4]

## 5. Conclusions and Recommendations

The optical image remapping technique and correlation examples presented in this report provides a method for performing in-plane, scale and rotation invariant target recognition with an optical BPOF correlator. Experiments need to be performed to prove the concepts presented in this paper will work with optical correlators. Further refinement of the optical image remapper include more phase levels in the CGH and a design which provides a complete image replication on the $\theta$-axis. Further quantitative data about the system's accuracy in determining scale and rotation needs to be measured. This accuracy may be highly dependent on the accuracy of the coordinate transform device or on the resolution of the output of the correlator . Finally, interfacing the optical image remapping system to a BPOF optical correlator or optical neural network pattern recognition system will be useful to determine the speed and accuracy of a machine vision system for determining the rotation and scale of objects of interest at an instant in time. Successful implementation of this technique shows great promise in machine vision applications for identifying objects at varying distances and orientations. A further extension of the log-polar remapping is for determining time-to-impact for autonomous platforms. Therefore, use in automatic target recognition of non-cooperative targets on the modern battlefield is a possibility if further refinements are successful.

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## Appendix A
## Binary Phase-Only Filter Correlation Program

```
% Binary Phase Only Filter Correlator Simulation
%       Version 2.2
%
%       Mark Getbehead
%       11 Jan 93
%
resultsnr = zeros(0,0);
resultcol = zeros(0,0);
resultrow = zeros(0,0);
resultpk = zeros(0,0);

file = 'ne';                          % File Prefix of Data Set

load filt2.mat                        % Load filter(Mat file)

for theta=0:30:330
I=zeros(128,128);
Iff=zeros(128,128);
output = zeros(128,128);
theta
eval(['load ',file, int2str(theta),'.dat']);      % Load image (Text file)
I = eval([file, int2str(theta),' ./ 255']);       % Make images 1 & 0's
I= fft2(I);
Iff=fftshift(I);
corr=Iff.*filt2;                % Multiply fft  by complex conj filter
corrl=fftshift(fft2(corr));      % Inverse fourier transform (last lens)
output=abs(corrl);              % sqrt(q.*conj(q))  find magnitude
output=output.^2;               % Mag squared for detector
clear I Iff corr corrl

eval('snr');
eval(['save necor',int2str(theta), '.txt output /ascii']);

% Append this loops results to array of past results
resultsnr = [resultsnr; SNRh];
resultcol = [resultcol; peakcol];
resultrow = [resultrow; peakrow];
resultpk = [resultpk; peakval];

clear  peakval SNR peakrow peakcol output
eval(['clear ', file, int2str(theta)]);
end

eval(['save ', file, 'snr.txt resultsnr /ascii']);
eval(['save ', file, 'col.txt resultcol /ascii']);
eval(['save ', file, 'row.txt resultrow /ascii']);
eval(['save ', file, 'pk.txt resultpk /ascii']);
clear theta filt2
```

## Appendix B
## Binary Phase-Only Filter Generation Program

```
% Matlab script to generate BPOF filter.
%  gen_bpof.scr
%
%       Mark Getbehead
%       11 Jan 93
%
f=input('Create filter from what file (no extension)? ','s');
eval(['load ',f,'.dat']);                    % Load file

F=eval(['fft2(',f,')']);          % Perform FFT on input matrix
Fsh = fftshift(F);                  % Flip matrix around
clear f F

%Fstar= conj(Fsh);

Fr=real(Fsh);
Fb=sign(Fr);                  % If <0 then -1, if >0 then 1
filt2=Fb>0;                   %  Change matrix into 0's and 1's
filt2 = filt2 .* 2;
filt2 = filt2 - 1;

clear Fsh Fr Fb
save filt2.mat filt2          % /ascii  Save filter as Mat file.. filt2.mat
clear filt2
```

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